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A Comparative Study of Cost Estimation Models used for Preliminary Aircraft Design

Rashid Ali [α] & Omran Al-Shamma [σ]

Abstract- Estimation of the direct operating cost (DOC), seat mile cost (SMC) and price of the aircraft, is an important aspect in commercial transport aircraft design. The operating costs are classified into two categories which are direct operating cost (DOC) and indirect operating cost (IOC). IOC is difficult to estimate well, since it depends on the services that the airline (customer) offered, and can vary considerably between operators. Therefore, DOC is useful and widely-used parameter for comparative analysis. Many methodologies have been developed to estimate DOC. There are three common methodologies that are in use in preliminary aircraft design. These models, namely the ATA, NASA and the AEA form the basis of cost estimation. In the preliminary aircraft design stage, cost estimates are required to evaluate the viability of the design being considered. This paper presents the cost estimation methodology of these three methods and compares the estimated costs for a range of current aircraft. The paper also presents a new empirical relationship for estimating the DOC.

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NOMENCLATURE

C_{AC} = aircraft cost
C_{AF} = airframe cost
C_{AFc} = airframe cost per kilogram
$C_{(al)_{kh}}$ = airframe labour manhours per flight hour
$C_{(al)_{kc}}$ = airframe labour manhours per flight cycle
$C_{(am)_{kh}}$ = airframe material cost per flight hour
$C_{(am)_{kc}}$ = airframe material cost per flight cycle
$C_{(el)_{kh}}$ = engine labour manhours per flight hour
$C_{(el)_{kc}}$ = engine labour manhours per flight cycle
$C_{(em)_{kh}}$ = engine material cost per flight hour
$C_{(em)_{kc}}$ = engine material cost per flight cycle
C_{al} = airframe labour maintenance cost per flight
C_{am} = airframe maintenance cost per flight
C_{amm} = airframe material maintenance cost per flight
C_{bur} = maintenance burden cost
C_{cc} = cabin crew cost
C_{dp} = depreciation cost per flight
C_{el} = engine labour maintenance cost per flight
C_{em} = engines maintenance cost per flight
C_{emm} = engine material maintenance cost per flight
C_{eng} = engine cost
C_{engc} = engine cost per one pound thrust
C_{fc} = flight crew cost
C_{fu} = fuel cost per gallone
C_{fuel} = fuel cost per flight
C_{grd} = ground − handling cost per flight
C_{ins} = insurance cost per flight
C_{int} = interest cost per flight
C_{lf} = landing fees per flight
C_{lr} = labour cost per hour
C_{maint} = total maintenance cost
C_{nav} = navigational charges per flight
C_{oil} = oil cost per gallone
E_{bpr} = engine bypass ratio
E_{oapr} = overall compressor ratio
F_i = international salary premium (= 1 for domestic,
= 1.1 for international flights
N_c = number of compressor stages per engine
N_{cc} = number of flight attendants
N_{eng} = number of engines
N_{fc} = number of flight crew
P_{af} = airframe life (Liebeck assumes 15 years)
P_{eng} = engine life (Liebeck assumes 15 years)
R = residual aircraft value (%)
R_{ins} = insurance rate
R_{int} = interest rate
S_{af} = airframe spares (assume $0.06 \times$ airframe cost)
S_{eng} = engine spares (assume $0.23 \times$ engine cost)
T_{eng} = engine thrust
U = aircraft utilization (hours/year)
m_{af} = aircraft empty mass minus engines mass (lbs)
m_{fuel} = design fuel mass
m_{lan} = landing aircraft mass
m_{oe} = aircraft operating empty mass
m_{pay} = payload mass
m_{to} = maximum takeoff weight
s_l = main mission stage length
t_B = block time in hours
t_f = flight time in hours

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I. Introduction

Direct operating cost and seat mile cost are significant parameters in evaluating competitive aircraft designs. Although the rule of thumb is that the aircraft cost depends mainly on aircraft empty weight, but occasionally this is not correct. For example, when new technologies and materials (e.g. composite) are used, it has an effect of reducing the aircraft weight, but may incur an increased production cost. Therefore, manufacturers always pick the design and price that maximizes their own return. This requires better estimates of the operating costs (OC) and good measure of the market elasticity. Customers are interested in cost savings, not just low aircraft price at the time of purchase but also throughout the lifetime of the aircraft [1]. More specifically, one pays for a pound of aluminium in the wing once, but a pound of fuel on every flight [2].

Aircraft operating costs consist of many items such as depreciation, insurance, maintenance, fuel burn, flight crew, cabin crew, landing fees, and passenger services. These items are grouped into two main categories which are direct operating cost (DOC) and indirect operating cost (IOC). IOC is difficult to estimate well, since it depends on the services that the airline (customer) offers [2]. Therefore, DOC and aircraft price is useful and widely-used parameter for comparative analysis.

In 1944, the Air Transportation Association of America (ATA) developed the first set of empirical equations to estimate DOC. It continued periodically to revise these formulae to match current statistical cost data. The last updated version was published in 1967 [3]. Many methodologies have been developed thereafter [4, 5]. Purpose of applying a standard methodology to estimate DOC is to enable efficient means for comparing the DOC of the competitive aircraft under set of conditions, and to enable both the manufacturer and the customer in assessing the economic suitability of the aircraft operation on a given route. For educational environments, ATA pointed out that it *"must essentially be general in scope, and for simplicity should preferably employ standard formulae into which the values appropriate to the aircraft under study are sub¬stituted"* [3]. Typically, aircraft manufacturers use standard methodologies in their cost comparisons, while customers (airlines) always generate their own methodologies based on many things that may not be accounted for, such as fleet size, route structure, accounting procedures, etc, or capitalize certain costs which then can be reported in depreciation or amortization cost figures.

II. Cost Estimation

Cost estimation model is an important aspect in educational commercial aircraft design, especially when the techniques are embedded in an automated design tool. It has been employed in interactive aircraft design software (iADS) [6]. This paper encapsulates three common methodologies and evaluates their effectiveness in estimating the DOC as proposed by ATA [3], NASA [7], and AEA [8]. Their empirical formulae are explained in details. ATA, the professional society of airline business in the U.S., used industry-wide statistical data to develop a standard methodology for estimating comparative DOC of jet aircraft. NASA's methodology is an estimation methodology known as DOC+I (Direct Operating Cost plus Interest). It is based on the work done by Liebeck [7], who was able to draw upon the operating costs of McDonnell Douglas aircraft in commercial service up until 1993. It is therefore based on a more recent set of data which reflect airline costs in a deregulated environment. AEA methodology has been accepted as the basis for comparison in Europe. These methodologies depend initially on estimating aircraft price (capital cost). It has a great impact on DOC. Estimating aircraft price in the early stages of the aircraft design requires an investigation of the actual data available. Prices of the current Boeing [9] and Airbus [10] aircraft for the year 2010 are shown as Figure 1, as a function of their operating empty weight. These prices have been shown as an average, since the exact price of a given aircraft depends upon special equipment particular to different buyers. It must be noted that year 2010 is chosen as a reference year due to the last available published data. Although some of DOC items have up-to-date values such as fuel price, others such as labour cost have not. The flexibility of the used models makes them applicable to be used for any year by applying a simple inflation factor. Simple inflation is applied by multiplying each DOC component in the model by the consumer price index (CPI) for the required year divided by the CPI for the reference year (2010). Aircraft price is evaluated by Sforza [11] in terms of \$/lb. It is being proposed here that aircraft price (in \$) should be evaluated as a function of the operating empty weight m_{oe} kg directly as defined by the proposed empirical formula (1) & (2).

$$C_{AC} = 10^6 \times (1.18 \times m_{oe}^{0.48} - 116),\ if\ m_{oe} \geq 10000\, kg \tag{1}$$

$$C_{AC} = -0.002695 \times {m_{oe}}^2 + 1967 \times m_{oe} - 2158000,\ if\ m_{oe} < 10000\, kg \tag{2}$$

Similar procedure was proposed by Kroo [12] to estimate the price of the aircraft's engine as a function of engine thrust, as shown in Figure 2. The equation is based on prices as in 1990 and should be corrected to prices of 2010 by applying a simple inflation multiplier (1.76) which is the ratio of the CPI for year 2010 to that for 1990. Ref. [13] presents some deflators that are used in the aerospace industry while more extensive information on the CPI and other economic factors may be found in [14]. The formula for engine price (in $) is:

$$C_{eng} = 1.76 \times 82.5 \times T_{eng} \tag{3}$$

III. DOC COMPONENTS

DOC is expressed in terms of $/hour, $/mile, ¢/seat-mile, or for cargo aircraft in terms of ¢/ton-mile. Costs in terms of $/mile indicate the maximum loss with a partially filled aircraft, while costs per unit productivity such as ¢/seat-mile, or ¢/ton-mile are indicative of the fare that must be charged with reasonable load factors. DOC breaks down into its components and is explained in the following sub-sections. Each component cost is computed using the three methodologies: ATA, NASA, and AEA, the respective formulae are presented for completeness. Aircraft speed is one of the important factors in calculating DOC components. It is calculated as by dividing the stage length by the block time [3]. The block time being composed of the sum of ground manoeuvre time (in hours – which includes one minute for takeoff = 0.25 for all aircraft), climb time, cruise time, descend time, and the time for air manoeuvre (which is six minutes - no credit for distance = 0.1 for all aircraft).

It must be pointed out here that all component costs are per trip and some of them are based on evaluation of the annual utilization (U) of the aircraft, which in turn depends mainly on the customer and its route (i.e. the range). The latter can be derived in terms of block hour time t_B.From the original ATA graph [3], the following formula represents the relationship between the block time and the annual utilization:

$$U = 6100 - 3100 \times t_B{}^{-0.3342} \tag{4}$$

MIT [15] developed the daily utilization for a number of US airliners in year 2006. It is based on average utilization of 10.64 hours/day, which is approximated to an annual utilization of about 3800 hours/year. It seems approximately equal to the average of the original utilisation proposed by the ATA method.

NASA suggests values of utilization as trips per year, for short range aircraft 2100 trips/year, medium range aircraft = 625 trips/year and for long range aircraft 480 trips/year. For short and medium ranges, AEA utilization(U)formula in terms of hours/year is:

$$U = \left(\frac{3750}{t_B + 0.5}\right) \times t_B \tag{5}$$

While for long range, it is assumed to be equal to 4800 hours/year. Equations (4) and (5) adjust the utilisation based on the block time, rather than adopt a fixed value, as outlined by the NASA method.

a) Depreciation

The Depreciation of the capital value of an aircraft is dependent to a large degree on the individual airline and its competitive conditions as the aircraft is maintained in a fully airworthy condition throughout its life. ATA depreciation period (D_a) is 12 years and 0% is the residual value for subsonic aircraft and its components [3]. ATA depreciation formula is:

$$C_{dp} = \frac{(C_{AC} + 0.1 \times C_{AF} + 0.4 \times C_{eng}) \times t_B}{D_a \times U} \tag{6}$$

Corresponding formula for NASA methodology is:

$$C_{dp} = \frac{C_{dp\,year}}{U} \tag{7}$$

Where $C_{dp\,year}$ is evaluated using the following formula:

$$C_{dp\,year} = (1 - R) \times \left(\frac{C_{AF}}{P_{af}}\right) + S_{af} \times \left(\frac{C_{AF}}{P_{af}}\right) + \frac{C_{eng}}{P_{af}} + S_{eng} \times \left(\frac{C_{eng}}{P_{eng}}\right) \tag{8}$$

AEA suggests a ten-aircraft fleet with 14-year lifespan and a residual value (R) of 10% of the total investment. i.e.:

$$C_{dp} = \frac{0.9 \times t_B (C_{AC} + 0.1 \times C_{AF} + 0.3 \times C_{eng})}{14 \times U} \tag{9}$$

b) Hull Insurance

ATA insurance value per trip [3] is determined as follows:

$$C_{ins} = \frac{t_B \times R_{ins} \times C_{AC}}{U} \tag{10}$$

Where R_{ins} is typically equal to 0.0023 [16]. NASA formula is:

$$C_{ins} = \frac{0.0035 \times C_{AC}}{U} \tag{11}$$

AEA formula is:

$$C_{ins} = \frac{0.005 \times C_{AC}}{U} \tag{12}$$

c) Interest

Although the original ATA method did not include the interest cost, most aircraft purchases nowadays are financed through the use of long-term debt and a down payment from company funds. For that reason, Hays [17], suggests the following AEA formula to be used in ATA methodology with R_{int} is typically = 0.07 [16]:

$$(C_{int})_{ATA} = \frac{t_B \times R_{int} \times (C_{AC} + 0.1 \times C_{AF} + 0.3 \times C_{eng})}{U} \tag{13}$$

$$(C_{int})_{NASA} = \frac{R_{int} \times (C_{AC} + 0.06 \times C_{AF} + 0.23 \times C_{eng})}{U} \tag{14}$$

Where R_{int} = 0.055[7].

AEA formula is similar to equation (11) with R_{int} = 0.053.

d) Flight Crew

ATA method for estimating the crew costs are based on the 1967 labour costs and the result must be updated to the 2010 prices. It is convenient to simply inflate the equation result by the ratio of consumer price index (CPI) in 2010 to that in 1967 which is:

$$(CPI)_{2010}/(CPI)_{1967} = 218.056/33.4 = 6.53$$

This factor modifies ATA formula to be including a multiplier for CPI of 100;

$$C_{fc} = t_B \times \left(\frac{0.326 \times m_{to}}{1000} + 653\right) \tag{15}$$

Whereas NASA's Equation, for estimating the crew costs is:

$$C_{fc} = t_B \times N_{fc} \times F_i \times \left(440 + \frac{0.532 \times m_{to}}{1000}\right) \tag{16}$$

Where m_{to} is in pounds.

AEA uses \$493 per block hour for a two-crew operation, i.e.:

$$C_{fc} = t_B \times 493 \tag{17}$$

e) Cabin Crew

In the ATA estimation method cabin crew costs are classified as indirect costs and hence, there is no formula for these costs. In the NASA methodology, the formula for cabin crew cost is:

$$C_{cc} = t_B \times N_{cc} \times C_{cc_b} \tag{18}$$

Where C_{cc_b} = base cabin crew cost of \$60/hr for domestic flights and \$78/hr for international flights.

AEA formula is similar to NASA except that AEA uses \$81/hr for C_{cc_b}.

f) Fuel and Oil

The current fuel prices may be found from IATA website [18]. A factor of 0.326 is used to convert 1kg of fuel weight to 1gal of volume for the reason that the density of Jet A fuel may be taken as 6.76 lbs/gal at standard conditions. On the other hand, examination of prices for turbine oil shows that it is around \$50/gal. Therefore, applying simple CPI inflation is sufficiently accurate and that the lubricating oils are not following the rise of fuel prices. ATA equation [3] for fuel and oil cost per trip (which includes 2% non revenue flying and assuming that the rate of consumption of oil is 0.135 lbs/hr/engine) is:

$$(C_{fuel})_{ATA} = 1.02 \times \left(m_{fuel} \times C_{f_b} + 0.135 \times t_B \times N_{eng} \times C_{oil}\right) \tag{19}$$

Where$C_{f_b} = 2.15\ \$/gal$ is the average value for year 2010, and $C_{oil} = 50\ \$/gal$.

Corresponding NASA and AEA Equation is:

$$C_{fuel} = \frac{m_{fuel} \times C_{f_b}}{\rho_f} \tag{20}$$

Where m_{fuel} is in pounds and excluding reserves, while $\rho_f = 6.7\ lbs/gal$.

g) Maintenance

This term includes labour and material costs for both airframe and engines. Furthermore, burden costs are also included i.e.:

$$C_{maint} = (C_{al} + C_{amm}) + (C_{el} + C_{emm}) + C_{bur} \tag{21}$$

i. *Airframe Labour Cost*

Labour cost associated for maintaining the airframe for the three methods is:

$$(C_{al})_{ATA} = \left(C_{(al)_{kh}} \times t_f + C_{(al)_{kc}}\right) \times C_{lr} \times M^{1/2} \tag{22}$$

Where $C_{(al)_{kc}} = \frac{0.05 \times m_{af}}{1000} + 6 - \frac{630}{\left(\frac{m_{af}}{1000} + 120\right)}$ (23)

$$C_{(al)_{kh}} = 0.59 \times C_{(al)_{kc}} \ ) \ , \tag{24}$$

$C_{lr} = \$42\ /hr$, and M=Cruise Mach Number

$$(C_{al})_{NASA} = \left(\left(1.26 + 1.774 \times \left(\frac{m_{af}}{10^5}\right) - 0.1071 \times \left(\frac{m_{af}}{10^5}\right)^2\right) \times t_B + \left(1.614 + \quad 0.7227 \times \left(\frac{m_{af}}{10^5}\right) + 0.1204 \times \left(\frac{m_{af}}{10^5}\right)^2\right)\right) \times C_{lr} \tag{25}$$

Where, $C_{lr} = 25 \frac{\$}{hr}$

AEA estimates C_{al} as:

$$(C_{al})_{AEA} = \left(\frac{\left(0.09 \times m_{af} + 6.7 - \frac{350}{m_{af} + 75}\right) \times (0.8 + 0.68 \times (t_B - 0.25))}{t_B}\right) \times C_{lr} \tag{26}$$

Where, $C_{lr} = 63 \frac{\$}{hr}$

ii. *Airframe Material Cost*

ATA estimation of C_{amm} is based on:

$$C_{amm} = C_{(am)_{kh}} \times t_f + C_{(am)_{kc}} \tag{27}$$

Where $C_{(am)_{kh}} = \frac{3.08 \times C_{AF}}{10^6}$, and $C_{(am)_{kc}} = \frac{6.24 \times C_{AF}}{10^6}$

Whereas NASA estimates it as:

$$C_{amm} = \left(\left(12.39 + 29.8 \times \left(\frac{m_{af}}{10^5}\right) + 0.1806 \times \left(\frac{m_{af}}{10^5}\right)^2\right) \times t_B + \left(15.2 + 97.33 \times \left(\frac{m_{af}}{10^5}\right) - 2.862 \times \left(\frac{m_{af}}{10^5}\right)^2\right)\right) \times 1.509 \tag{28}$$

Correspondingly AEA determines it to be:

$$C_{amm} = \left(\frac{4.2 + 2.2 \times (t_B - 0.25)}{t_B}\right) \times \left(\frac{C_{AF}}{10^6}\right) \tag{29}$$

iii. *Engines Labour Cost*

For the three methodologies it is estimated as:

$$(C_{el})_{ATA} = \left(C_{(el)_{kh}} \times t_f + C_{(el)_{kc}}\right) \times C_{lr} \tag{30}$$

Where $C_{(el)_{kh}} = \left(0.6 + \frac{0.027 \times T_{eng}}{10^3}\right) \times N_{eng}$ (31) And $C_{(el)_{kc}} = \left(0.3 + \frac{0.03 \times T_{eng}}{10^3}\right) \times N_{eng}$ (32)

$$C_{el})_{NASA} = \left(0.645 + \left(\frac{0.05 \times T_{en\,g}}{10^4}\right) \times \left(0.566 + \frac{0.434}{t_B}\right)\right) \times N_{eng} \times C_{lr} \times t_B \tag{33}$$

$$(C_{el})_{AEA} = 0.21 \times C_1 \times C_3 \times C_{lr} \times \left(1 + T_{eng}\right)^{0.4} \tag{34}$$

Where $C_1 = 1.27 - 0.2 \times E_{bpr}{}^{0.2}$ (35)

And $C_3 = 0.032 \times N_c + K$ (36)

iv. *Engines Material Cost*

The material cost mainly being function of number of engines, block time, thrust and Initial engine cost, the three methods estimate it as:

$$(C_{emm})_{ATA} = C_{(em)_{kh}} \times t_f + C_{(em)_{kc}} \tag{37}$$

Where $C_{(em)_{kh}} = 2.5 \times N_{eng} \times \left(\frac{C_{eng}}{10^5}\right)$ (38)

and $C_{(em)_{kc}} = 2 \times N_{eng} \times \left(\frac{C_{eng}}{10^5}\right)$ (39)

$$(C_{emm})_{NASA} = \left(\left(25 + \left(\frac{0.05 \times T_{eng}}{10^4}\right)\right) \times \left(0.62 + \frac{0.38}{t_B}\right)\right) \times N_{eng} \times t_B \times 1.509 \tag{40}$$

$$(C_{em})_{AEA} = 2.56 \times C_1 \times (C_2 + C_3) \times \left(1 + T_{eng}\right)^{0.8} \tag{41}$$

Where $C_2 = 0.4 \times \left(\frac{E_{oapr}}{20}\right)^{1.3} + 0.4$ (42)

C_1 & C_3 as in Equation (35) & Equation (36) respectively.

Note that AEA total engine maintenance (labour + material) is:

$$(C_{em})_{AEA} = N_{eng} \times (C_{el} \times C_{emm}) \times \left(\frac{t_f + 1.3}{t_f - 0.25}\right) \tag{43}$$

v. *Maintenance Burden*

It is defined as labour and material overheads that contribute to overall maintenance costs through activities such as administration, controlling, monitoring, planning, testing, and tooling. It is also called “Indirect Maintenance Cost”.

$$(C_{bur})_{ATA} = 1.8 \times (C_{al} + C_{el}) \tag{44}$$

$$(C_{bur})_{NASA} = 2 \times (C_{al} + C_{el}) \tag{45}$$

AEA has no burden cost included in its methodology.

h) Landing Fee

The landing fee is based on the maximum landing weight for domestic operations, or maximum takeoff gross weight for international operations. They may vary significantly in Europe, with possible additional fees such as for NO_x emissions or community noise, which are not included in DOC. ATA methodology categorized landing fee as an indirect cost, so for the other two methods it is determined to be:

$$(C_{lf})_{NASA} = 2.2 \times \frac{m_{land}}{1000} \quad for\ domestic\ operations \tag{46}$$

$$(C_{lf})_{NASA} = 6.25 \times \frac{m_{to}}{1000} \quad for\ international\ operations \tag{47}$$

Note that the weights (m_{lan}, m_{to}) are in pounds (*lbs*). AEA formula is:

$$(C_{lf})_{AEA} = 7.8 \times \frac{m_{to}}{1000} \tag{48}$$

i) Navigation Fee

The navigation fee is based on the first 500nm of a trip and the maximum takeoff gross weight of the aircraft, and applies to international flights only. ATA categorized this cost as an indirect cost, so not part of the DOC estimation, hence for the other two methods while NASA formula is:

$$(C_{nav})_{NASA} = 0.2 \times 500 \times \sqrt{\frac{m_{to}}{1000}} \tag{49}$$

Note: m_{to} is in pounds (*lbs*) for (49) & (50)

$$(C_{nav})_{AEA} = 0.5 \times \frac{s_l}{1000} \times \sqrt{\frac{\frac{m_{to}}{1000}}{50}} \tag{50}$$

j) Ground Handling Fee

This cost is included in DOC in AEA methodology only using the following formula:

$$C_{grd} = 0.1 \times m_{pay} \tag{51}$$

k) DOC

The total DOC per flight for the three methodologies therefore becomes:

$$(DOC/flight)_{ATA} = C_{dp} + C_{ins} + C_{fc} + C_{fuel} + C_{maint} \tag{52}$$

$$(DOC/flight)_{NASA} = C_{dp} + C_{ins} + C_{fc} + C_{fuel} + C_{maint} + C_{int} + C_{cc} + C_{lf} + C_{nav} \tag{53}$$

$$(DOC/flight)_{AEA} = C_{dp} + C_{ins} + C_{fc} + C_{fuel} + C_{maint} + C_{int} + C_{cc} + C_{lf} + C_{nav} + C_{grd} \tag{54}$$

Inspection of Equations (52), (53) and (54) reveals that $C_{int} + C_{cc} + C_{lf} + C_{nav}$ nav is the variation between the ATA and other methods, whereas C_{grd} is an additional factor when compared to the NASA method. This can be better seen from Figure 5. How will the numbers stack up?

IV. Results

To make a good comparison between ATA, NASA, and AEA methodologies, all of them have been applied to the current Airbus and Boeing aircraft. At a glance, AEA methodology gives the highest DOC values and in turn highest SMC as shown in Figure 3 and Figure 4, respectively. Although Figure 5 shows that AEA methodology has the highest DOC components and hence the highest value, it is better to break down the DOC into its main components and investigates each one.

The first component of DOC under consideration is the standing charges (or so-called the ownership) which consists of depreciation, insurance, and interest. These costs forms 30-40% of DOC and depend mainly on the annual utilization of the aircraft. Obviously, as the utilization increases, standing charges decreases. NASA methodology has the lowest average value, but the main drawback of NASA methodology is the ambiguous definitions of ranges (short, medium, and long) to find its utilization. On the other hand, if the aircraft is fully owned, interest is not included. From the engineering design point of view, Swan [19] suggests a simple way to overcome this problem by considering a monthly lease cost for new aircraft at about 0.8-0.9% of the aircraft price.

Maintenance cost is the second component that must be considered. In general, it makes up 13% of the DOC [19]. It is based on the utility of the aircraft which are in "steady-state maintenance". That means the maintenance savings of the first five years for new designed aircraft have been finished and the second half-life maintenance cycles has been initiated. Although the most expensive inspections occur once each 3-4 years, the average cost is usually a rule of thumb. The maintenance cost forms 20-25% of DOC for ATA, 8% for NASA, and less than 1% for AEA. These huge differences make the comparison meaningless.

Flight crew cost is another major component of DOC. It is based on both flight time and maximum take-off weight for ATA and NASA, while it is based only on flight time for AEA methodology. Although there is no much difference between ATA and AEA, MIT [15] data agrees completely with ATA.

Fuel cost has changed rapidly in the last 10 years and forms a significant parameter that affected the aviation market. There is no difference noticed between the three methodologies. Although ATA added the oil used cost to the fuel cost, but it is form a very small difference that can be discounted.

Now, the question is which of the three methods is suitable, that can be used in preliminary design phase? The answer is simple. Any of them can be used. The question now is more specifically: Which of them estimates the DOC close to the actual value? First of all, it is a generally accepted fact that all manufacturers have their own proprietary methods for cost estimation, dependent upon their costing methods and operations, and are not available to the general public. On the other hand, all published data comes from the customers (airlines). Again each airline has their own categories to classify the various DOC components. For educational purposes, Al-Shamma [20] presented the three methods in his interactive aircraft design software (iADS). It is the designer's responsibility to select one of them. The choice is somewhat dependent upon the various DOC components to be included. If for example, the design is a short range aircraft, then there is no navigation fee since it is applicable only to international long haul flights. For small business aircraft, no flight attendant cost required. If the requirements have no constraints on DOC components, only one method should used for all competitive aircraft designs. Figure 5 summarizes the DOC components for ATA, NASA, and AEA. It is shows that ATA has the lowest value, since landing fee, flight attendant cost, navigation fee, and ground handling cost are calculated as IOC. ATA methodology discounts the costs due to interest cost off.

Another methodology, which has been developed by Swan [19], was applied. It evaluates the DOC as a function of stage length and seat capacity. It is based on years 1999-2001 data, and need to apply an inflation factor of 1.266 to update data to year 2010. From Figure 6, it is clear that Swan's methodology gives approximately the same average difference when compared with the ATA methodology.

Figure 7 shows the average value of the DOC obtained by the three methods against the maximum takeoff weight m_{to}. A simple equation that yields an acceptable result in the conceptual design stage can be determined to be:

$$DOC/Flight = -4.497 \times 10^{-7} \times {m_{to}}^2 + 0.9588 \times m_{to} - 33214 \qquad (55)$$

V. Conclusion

DOC is a significant parameter in evaluating competitive aircraft designs and widely-used parameter for comparative analysis. ATA, NASA, and AEA are three common methodologies that are employed in the cost estimation for educational purposes and their choice depends upon the inclusion of various sub-categories that makes up the total DOC. All cost estimation methods have been applied to estimate the DOC and

SMC for the existing transport aircraft. The results show that ATA and NASA methodologies are close to each other. However, many factors (up to date) are required for DOC/SMC estimation. Hence, a very simple empirical relation was presented that estimates the DOC as a function of maximum takeoff weight, this can be very useful in conceptual or preliminary design phase.

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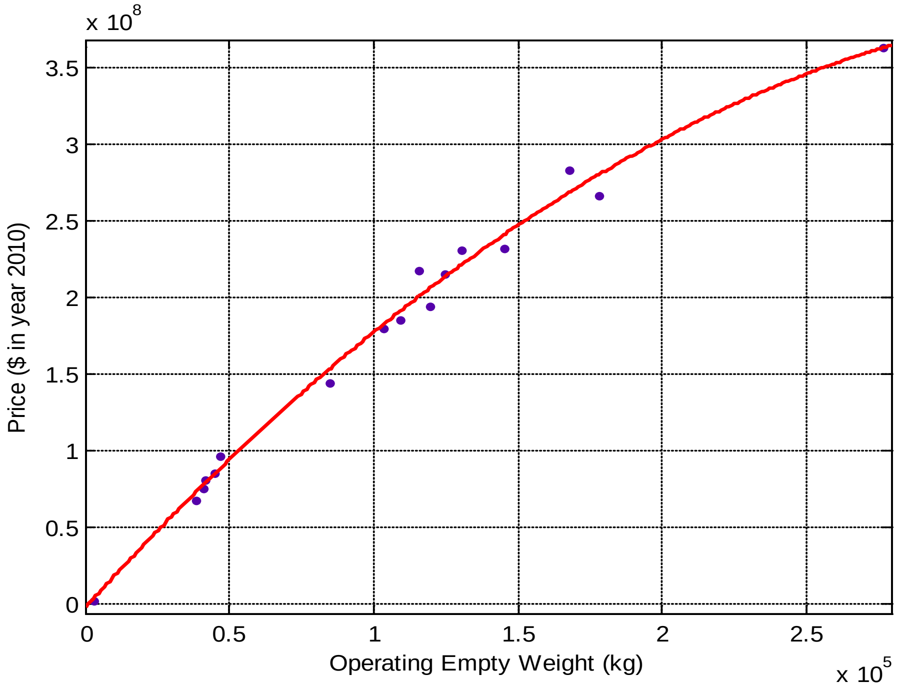

Figure 1 : Airbus & Boeing aircraft prices vs. Operating empty weight

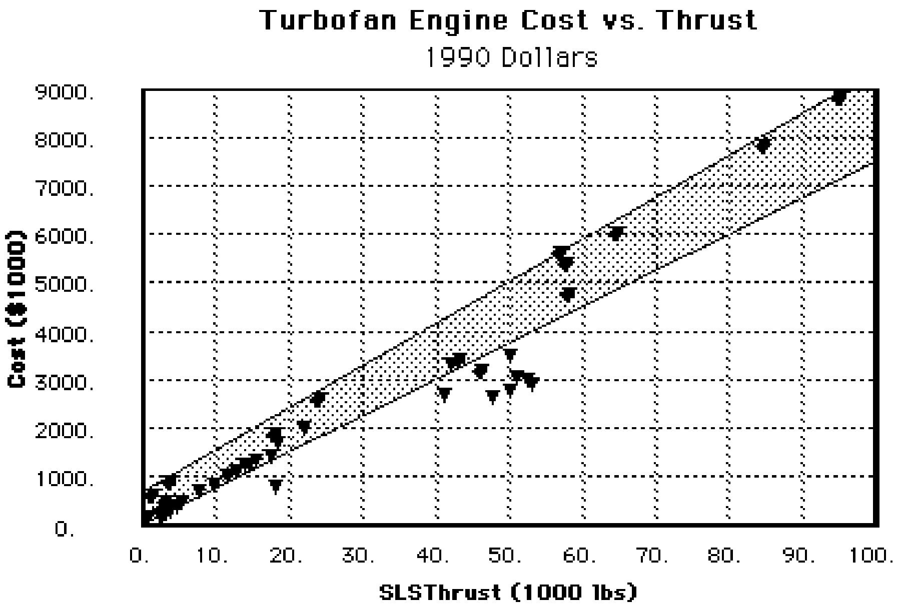

Figure 2 : Engine prices ($1990) vs. SLS thrust (lbs)

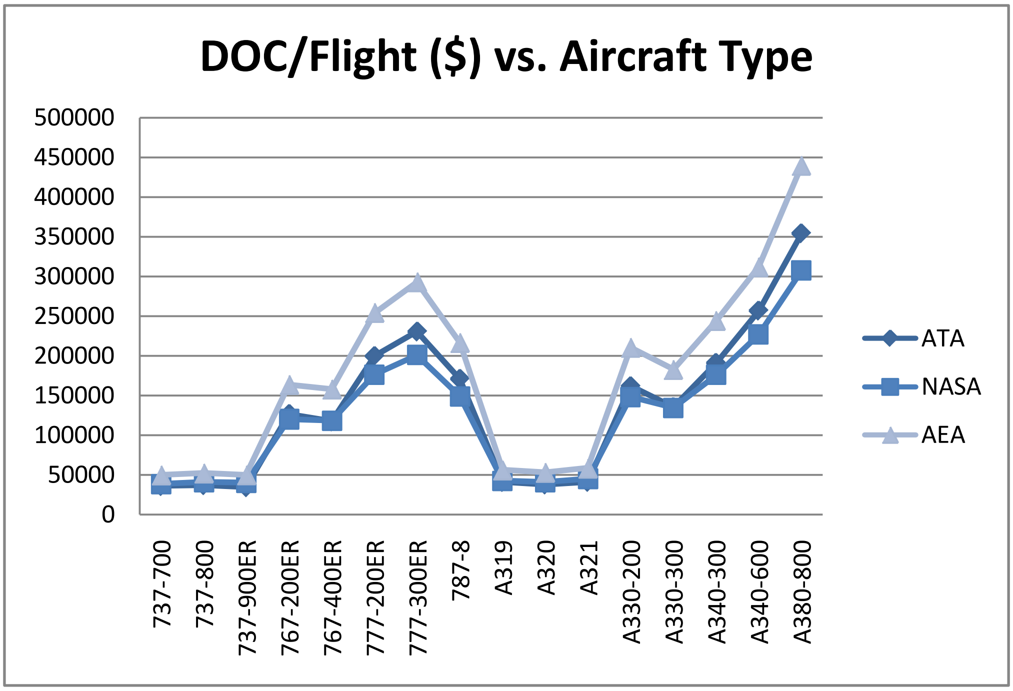

Figure 3 : DOC for ATA, NASA, and AEA methodologies

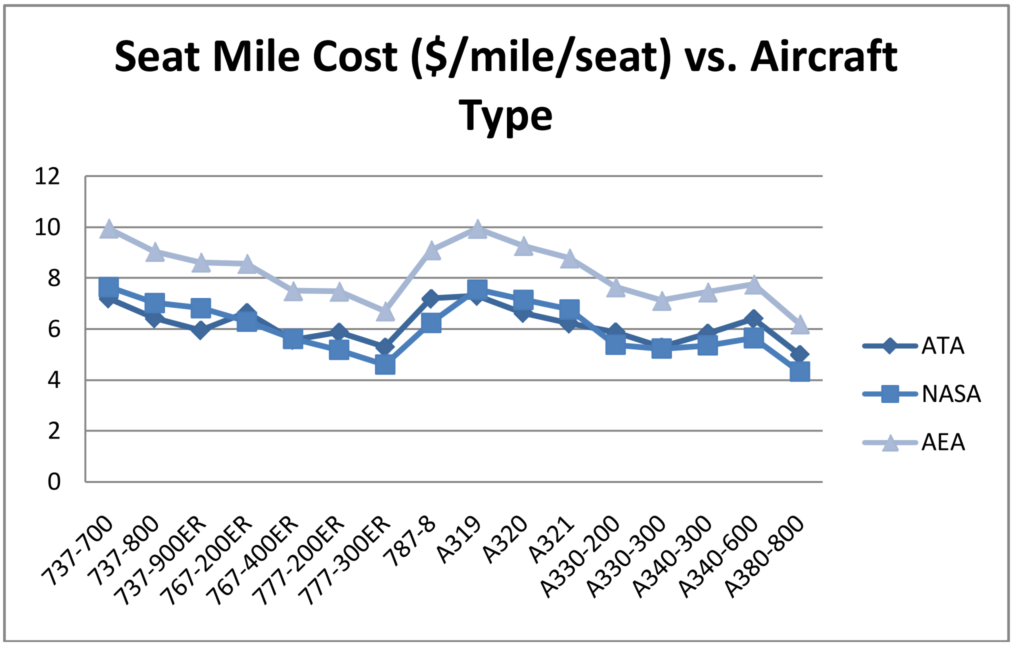

Figure 4 : SMC for ATA, NASA, and AEA methodologies

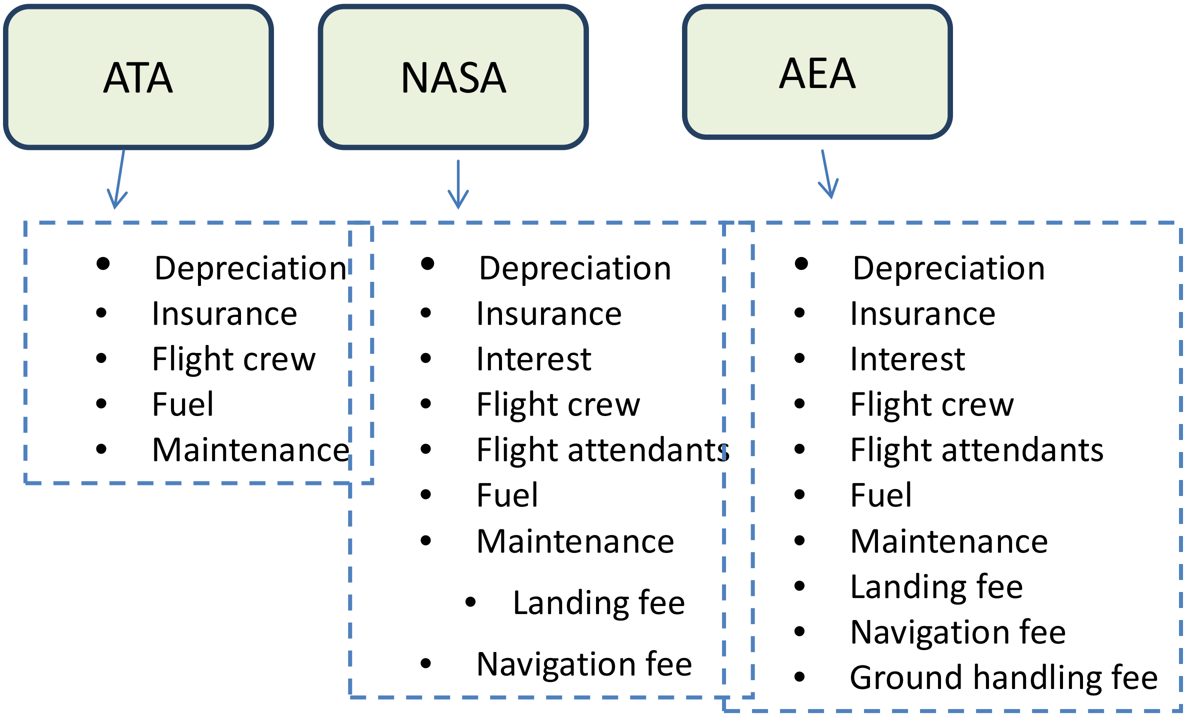

Figure 5 : DOC components for ATA, NASA, and AEA methods

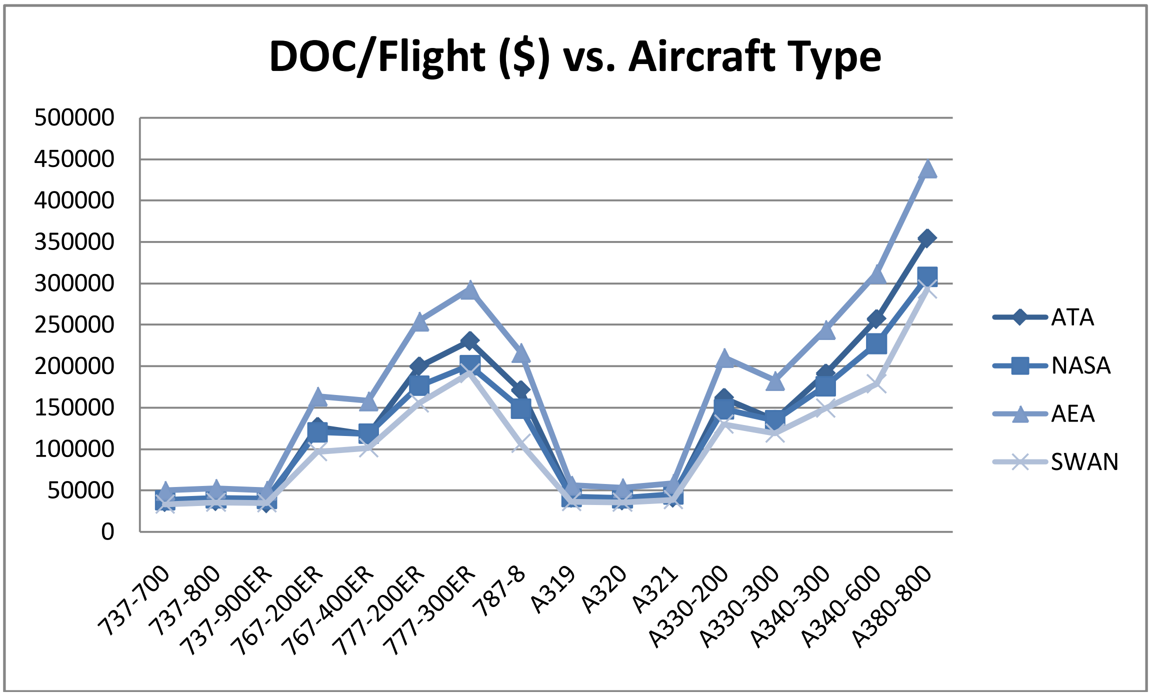

Figure 6 : DOC for ATA, NASA, AEA, and Swan methodologies

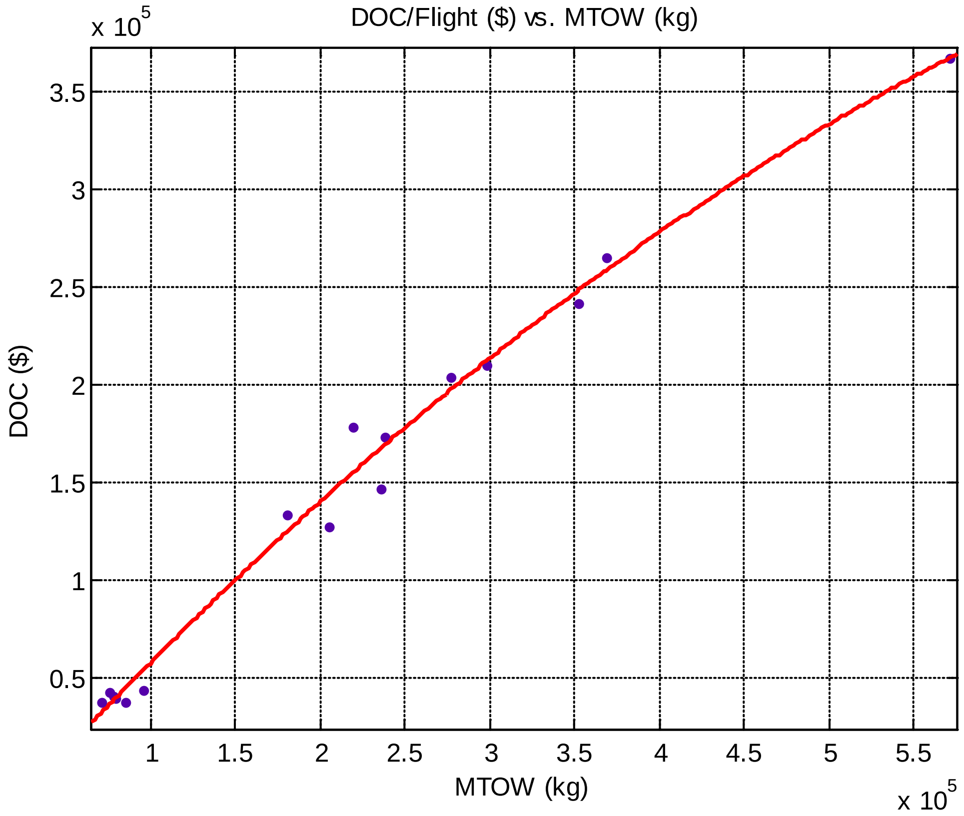

Figure 7 : Average DOC ((AEA+ATA+NASA)/3) versus Maximum takeoff weight (MTOW)